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Office of Scientific Research and Development

National Defense Research Committee

Division C - Section C - 4

"THE HIGH SPEED WATER TUNNEL at the CALIFORNIA INSTITUTE OF TECHNOLOGY"

prepared by

Robert T. Knapp
Vito A. Vanoni
James W. Daily

California Institute of Technology
Hydraulic Machinery Laboratory
Pasadena, California

Copy No. 17 June 29, 1942

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"THE HIGH SPEED WATER TUNNEL
at the
CALIFORNIA INSTITUTE OF TECHNOLOGY"

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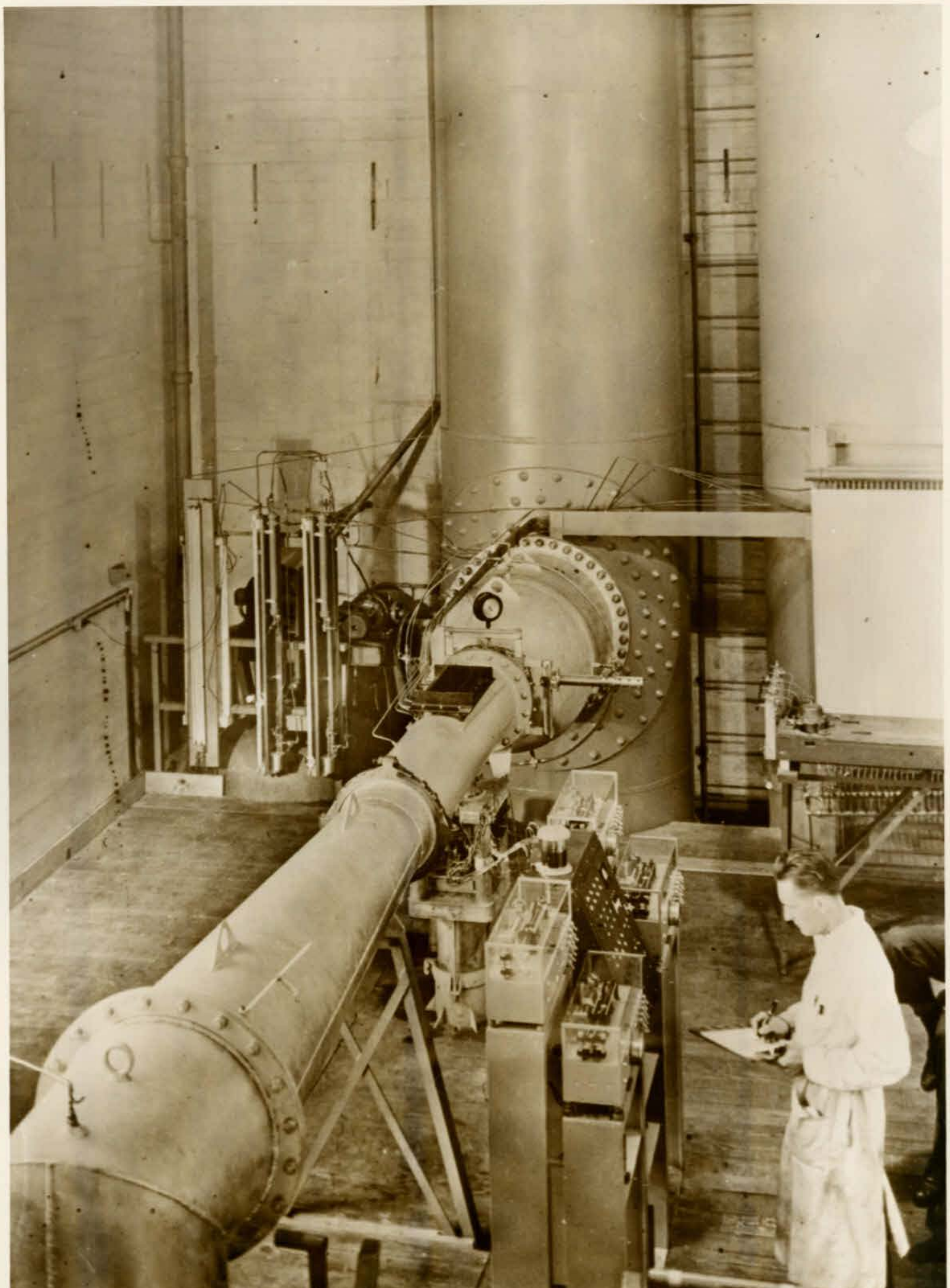

PREFACE

The high speed water tunnel described in this report has been constructed for Division C, Section C-4 of the National Defense Research Committee, under contract OEMsr - 207 with the California Institute of Technology. The request for these facilities originated with the New London Laboratory in connection with their work on underwater ordnance.

ABSTRACT

The high speed water tunnel was established at the California Institute of Technology to study the forces acting upon moving bodies immersed in a fluid. The working section of the tunnel is 14 inches in diameter and 6 feet long and velocities up to 72 feet per second are obtained in it. The model to be tested is mounted on the spindle of a three component balance which measures the drag force, the yaw or lateral force and the moment about the spindle support. The angle of inclination of the model to the flow direction can be adjusted easily. From these measurements are determined the magnitude and location of the resultant forces acting on the model.

In order to study cavitation, the pressure in the tunnel is made adjustable and a transparent working section is provided for visual and photographic observations.

For qualitative assistance in interpreting the results of the tunnel studies in terms of the effects of the body shapes on the flow pattern, an auxiliary flume is available. The flow is made visible by use of a new technique employing polarized light.

Frontispiece:

The High Speed Water Tunnel Operating Floor

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THE HIGH SPEED WATER TUNNEL AT THE CALIFORNIA INSTITUTE OF TECHNOLOGY

I. REVIEW OF NEEDS AND EXISTING FACILITIES

A. Needs of the NDRC

To Section C-4 of Division C of the NDRC has been assigned the study of methods of submarine detection and attack. In pursuing this objective, the Section, and particularly the New London Laboratories and the Morris Dam Project, found urgent need to study quantitatively the forces acting upon moving bodies immersed in a fluid. The main need was for information concerning bodies moving in water at reasonably high velocities, i.e., up to 60 feet per second or higher.

B. Survey of Existing Test Facilities

1. Wind Tunnels. Testing facilities of several different classes offer possibilities for making such measurements. The type most generally applicable is the wind tunnel. The fact that the fluid utilized is air instead of water is not in itself a disqualifying disadvantage. However, to obtain suitable testing conditions with air, it is necessary to use large sized models and high velocities. Under these conditions compressibility effects may become troublesome. One serious disadvantage is that cavitation effects cannot readily be studied, since this phenomenon, which is easily produced in water, does not occur in air. Another serious difficulty is that in this emergency period all existing wind tunnel facilities are being used to the limits of their capacity.

2. Open Water Channels. The open type hydraulic channel or flume offers possibilities for use. Flumes, ranging in cross-section from a square foot to about 100 square feet are available in many hydraulic laboratories. However, they all operate at low velocities, 5 feet per second being exceptionally high. In addition, the uniformity of flow is seldom satisfactory and the turbulence level is generally too high to make accurate measurements possible.

3. Propeller Testing Tunnels. The third possible class of testing equipment is the propeller testing tunnel. Since this type appears most nearly suitable for the purpose, the existing installations will be described briefly. Propeller tunnels basically are similar to wind tunnels, circulating water instead of air. Flow is obtained with a propeller pump. Provision is generally made to vary the pressure to facilitate cavitation studies. The testing section is designed for uniform velocity distribution and relatively low turbulence. The pro-

peller to be studied is mounted on the upstream end of an axial shaft which is arranged to measure torque and thrust.

When these tunnels are considered for measuring the dynamic forces acting upon submerged bodies, it is seen that they have limitations arising from the fact that they were designed for another purpose. These limitations are:

(a) Equipment is available for measuring drag forces only. Measurements of yaw forces and moments about axes normal to the flow would require complete new balances;

(b) The working section is short, thus making it unsuitable for the study of projectile and torpedo models unless the scale ratio is kept very small.

(c) The propeller tunnels in this country have "open-type" jets. The flow enters one side of a fairly large test chamber through a nozzle and is collected in a concentric diffuser section projecting from the opposite wall. The testing section, therefore, has no definite boundary. This is a disadvantage since the boundary effect which exists both for the open and the closed-type jet is indefinite and variable for the open jet, but is more specific and easier to compute for the closed one.

(d) The "open-type" test chamber may induce flow instability resulting in pulsations and variable velocities;

(e) Although the propeller tunnels have velocities sufficient to simulate extremely high ship speeds, the actual maximum velocities are all lower than those desired for the proposed investigations.

One further practical objection to the use of propeller tunnels for NDRC investigations is that they were all working to capacity on important propeller studies.

The following table summarizes the principal characteristics of the three main propeller testing tunnels:

Location	Diameter Test Jet	Length of Test Jet	Ratio of length to Diameter of Test Jet	Maximum Velocity
David Taylor Model Basin	12"	12" (±)	1 (±)	26 ft/sec
M. I. T.	20"	26"	1.3	33 "
David Taylor Model Basin	27"	39"	1.45	42 "

4. Ship Towing Tanks. The fourth class of equipment to be considered is the model basin or ship towing tank. Here the model is towed through still water by a travelling carriage. The balance mechanism for measuring forces is mounted on the carriage. In general, this balance is suitable only for floating models; whereas, for NDRC purposes, deeply submerged models are required. In certain towing tanks suitable balances have been constructed and used to study the performance of torpedoes.

Towing tanks are adapted to making measurements with full sized models. However, carriage speeds seldom exceed 25 knots which is lower than the desired range for normal studies, and is too low to obtain fully developed cavitation. Surface waves offer the same complications as they do in the open water channels. Finally, the question of availability is again very important since with a greatly accelerated shipbuilding program all available towing tanks are working on essential war problems.

5. Circulating Ship Testing Flumes. A fifth class of equipment should be mentioned briefly, although basically it belongs in the category of open water channels. This is the circulating flume designed for ship testing. For the study of ship models, this equipment seems to promise many advantages, such as speed of operation, ease of observation, and continuous performance instead of the individual run required in the towing tanks. For the NDRC studies, however, its only advantages over the regular hydraulic flume are a more uniform flow, a lower turbulence level, and higher speeds, although 10 knots is about the maximum contemplated. As far as is known, no such equipment is yet in existence in this country.

6. Free Fall Measurements. The sixth class of equipment for the study of the motion of submerged bodies consists basically of a tank or reservoir in which the flight of the bodies in free fall can be studied by various measuring instruments. This type of study is indispensable in the overall investigation since the integrated behavior of the body can be obtained. However, it is not adaptable to the determination of the individual forces or the quantitative influence of specific design features.

C. Summary of Existing Situation Previous to the Construction of The High Speed Water Tunnel

Based on the state of affairs as outlined, the conclusion reached was that there was no existing equipment available which was specifically adapted to the quick and accurate determination of the hydrodynamic characteristics of submerged bodies in motion and that the facilities most nearly suitable were being fully utilized in the war effort for the purposes for which they were primarily designed. Therefore, an NDRC project for construction of a high speed water tunnel and balance equipment was recommended.

II. OUTLINE OF CHARACTERISTICS REQUIRED FOR THE TUNNEL

A. General Requirements

The general requirements of the high speed water tunnel are:

(a) to determine the hydrodynamic forces acting upon submerged bodies such as projectiles, torpedoes, etc., both when the axes of such bodies are parallel to or inclined to the direction of motion;

(b) to furnish a means for systematically developing shapes to meet specific needs of stability, speed, and dynamic behavior.

As a result of a careful consideration of the requirements it was decided that the type of equipment most suitable would be a closed-circuit, closed-measuring-section, high speed water tunnel.

B. Detailed Requirements

1. Velocity. The lower limit of the acceptable maximum velocity was set at 50 feet per second since it is felt that existing developments showed a definite trend toward higher and higher velocities for service applications.

2. Dimensions of Measuring Section. The acceptable model sizes and scales determine the size of the tunnel. It is axiomatic that models should be kept as small as compatible with desired accuracy and reliability of the test results, since smallness makes for economy, speed, and flexibility, and therefore increases the productivity of the laboratory. It was estimated that the prototype diameters of the bodies to be studied would vary from 2 to 24 inches. Since the measurements are to be made in water, which is a fluid of high density and low viscosity, it was felt that a model diameter of 2 inches would result in forces of reasonable magnitude and at the same time the flow conditions would be comparable to service conditions. In other words, a 2 inch model tested in the high speed tunnel gives sufficiently large Reynolds Numbers to be comparable with prototype conditions.

On this basis it was decided that the working section should be 14" in diameter. This is in accordance with proven current wind tunnel practice for dirigibles and similar symmetrical bodies, i.e., a model diameter of about 15% of that of the measuring section.

Aerodynamic practice has shown that the test chamber should be considerably longer than the model if accurate drag measurements are to be obtained. The maximum prototype length was estimated to be 8 to 10 diameters, with average length 4 to 6 diameters. This would make the average model length 8 to 12 inches with extremes to 20 inches. For the NDRC work it was felt that a large working section would also permit more extensive observations of the wake. Therefore, a 72 inch working section was decided upon.

3. Type of Working Section. A closed-type working section was decided upon for the reasons already discussed. Briefly, these are that the closed-type section reduces the energy loss, gives more stable flow, and results in a more definite and calculable boundary correction to the measurements.

4. Balance Equipment for Force Measurements. The choice of the type of balance is one of the most difficult problems in connection with the tunnel. The balance is a necessary evil. The forces on the body under

study must be measured, but any connection to the body to provide means of measuring these forces changes the forces themselves and thus a correction must be made. An analysis of the measurement desired shows that the balance system can be relatively simple, since the bodies to be studied have axial symmetry. A three component balance, therefore, is capable of furnishing all of the necessary information since the possible forces acting on the body can be reduced to a drag force in the direction of flow, a yaw or lateral force, and a moment about an axis normal to the direction of flow. One additional factor enters into the selection of balance type. It is anticipated that it will be necessary to study the characteristics of propelled bodies, whether the force of propulsion comes from a propeller or a jet of fluid. This precludes the use of a balance which attaches axially to the rear of the body. The wire type balance attachments is also eliminated because it provides no possibility for introducing a supply of fluid for the driving jet. Therefore, a single spindle type balance was decided upon with the model axis normal to that of the spindle.

5. Requirements for Cavitation Studies. If submerged bodies are required to travel at high speeds near the water surface, cavitation may result and produce serious deviations from the expected performance. To be able to study the effects of cavitation in the model performance introduces two requirements: (a) that the absolute pressure in the measuring section be made variable without affecting the velocity of the flow, and (b) that provision be made for visual observation to observe the location and the action of the cavitation when it was produced.

III. DESCRIPTION OF EQUIPMENT AT THE CALIFORNIA INSTITUTE OF TECHNOLOGY

A. Existing Facilities

One of the reasons for constructing the high speed water tunnel at the California Institute of Technology was that the existing facilities of the Hydraulic Machinery Laboratory could be used to furnish a large part of the basic equipment necessary for the tunnel.[1] Such equipment includes:

(a) the electric dynamometer with its motor generator set and speed control system which furnishes a precision variable speed drive for the main circulation of the tunnel;

(b) the main pressure tank which has been incorporated in the tunnel circuit and serves as a stilling tank to obtain uniform flow in the testing section;

(c) the pressure control system. The function of this system remains unchanged: to control the absolute pressure in the system

* * * * * * * *

(1) For details of this equipment see "The Hydraulic Machinery Laboratory at the California Institute of Technology", by R. T. Knapp, Trans. A.S.M.E., vol.58, Nov.1936, pp. 663-676, a copy of which is incorporated as Appendix A. of this report.

independent of velocity so that cavitation can be produced or inhibited at will;

(d) the cooling system which dissipates the energy introduced by the main circulating pump and thus maintains a constant temperature;

(e) the weighing-type manometer and weighing-type pressure gages which have been incorporated into the velocity and force measuring systems for the tunnel.

A rough estimate indicates that the use of these items has resulted in a saving of two-thirds of the time and expense which would have been required otherwise.

B. Description of Tunnel

1. General Description Primary Flow Circuit. Figure 1 is an isometric diagram of the complete installation. The flow circuit can be traced by starting with the circulating pump. This is driven by the dynamometer through a multiple V-belt drive having a speed reduction of 2 to 1. The pump discharges horizontally to the right into a diffuser section from which it enters the 5-foot diameter vertical stilling tank. Here the flow rises until it reaches the inlet end of the working section. This consists of a short length of 34 3/4" pipe followed by a cast bellmouth nozzle, which reduces the flow passage to the 14-inch diameter of the working and testing section. The balance is seen located near the upstream end of the working section. From the working section the flow enters the horizontal diffuser, which reduces the velocity considerably before the vane elbow is encountered. After the elbow the flow passes into the downcomer, which completes the diffusion to the inlet diameter of the circulating pump.

Figure 2 shows this main circuit in more detail.

Figure 2 is a photograph of the completed tunnel.

Figure 4 shows a view of the Laboratory looking in the same direction before the tunnel construction was started.

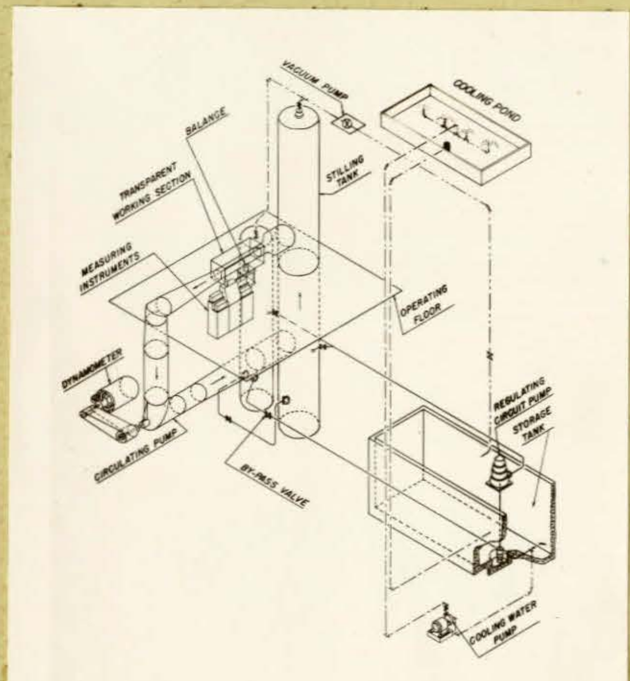


Fig. 1. Flow Circuits of the High Speed Water Tunnel

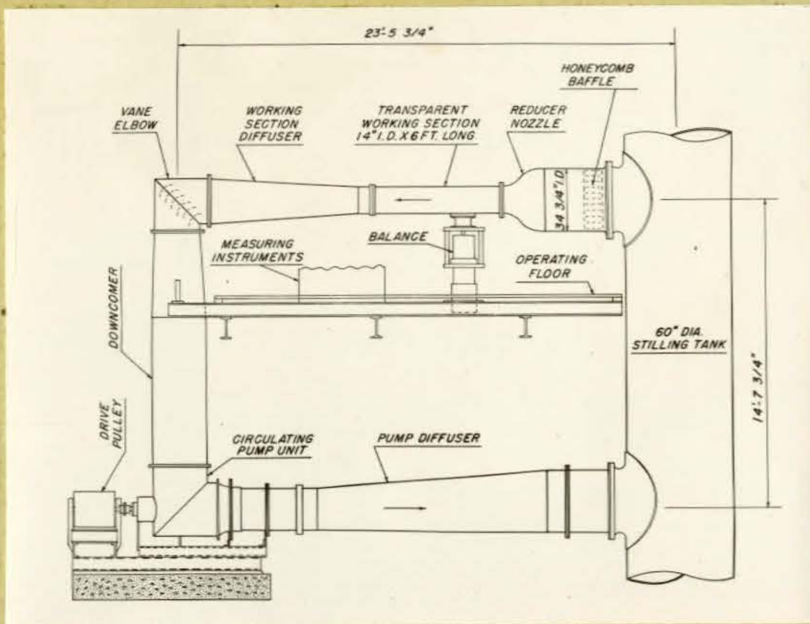


Fig. 2. Profile of Main Flow Circuit of the Water Tunnel.

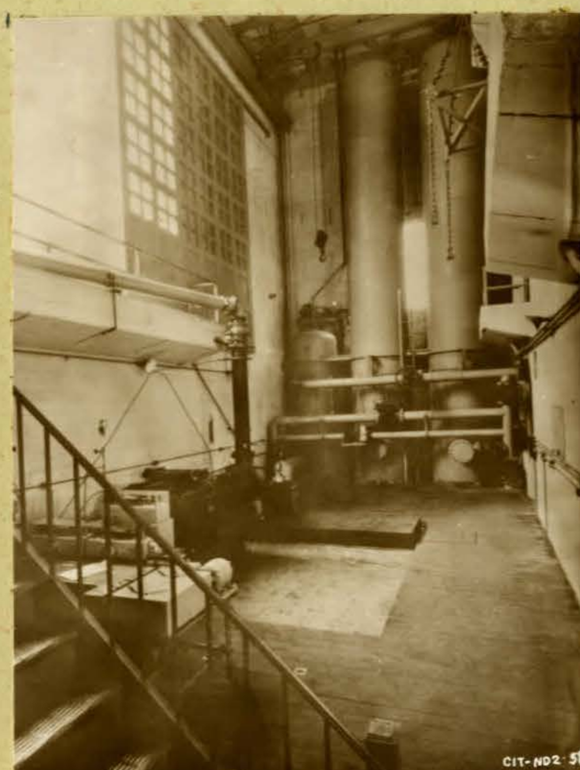


Fig. 3. View of Completed Tunnel Circuit.

Fig. 4. The Hydraulic Machinery Laboratory Before the Tunnel Installation.

(a) Circulating Pump. Figures 5 and 6 show two views of the circulating pump as it was mounted on its bedplate during the erection. Figure 5 shows the straightening vanes in the discharge piece; whereas Figure 6 is taken looking into the inlet flange. In this figure the vanes of the built-in elbow are clearly seen.

Figure 7 shows the V-belt drive from the dynamometer. Twenty belts are used in multiple for this drive which has a rated capacity of 250 horsepower. Since the center-line distance could not be adjusted, provisions have been made for an idler to take care of the belt tension. The dynamometer is cradle-mounted so that the horsepower for operating the tunnel may be measured readily.

Fig. 5. Tunnel Circulating Pump Showing Straightening Vanes in Discharge Piece.

(b) Stilling Tank. In order to utilize the existing high head tank of the Hydraulic Machinery Laboratory for the stilling tank of the tunnel it was necessary to install two large openings for inlet and outlet. Figure 8 shows these openings cut and drilled for the nozzle. Figure 9 shows the lower nozzle bolted in place, ready for rivets. The inside diameter of both nozzles is 34 3/4".

The stilling tank serves different purposes. First it reduces the velocity and the turbulence level before it enters the working section. Second, it acts as separator to remove any undissolved air which enters the system either by being injected into the model or by possible leaks at points where the pressure is subatmospheric. Since the discharge from

Fig. 6. Tunnel Circulating Pump View Showing Vaned Inlet Construction.

Fig. 7. V-Belt Drive for Circulating Pump.

Fig. 8. Nozzle Openings in Stilling Tank.

Fig. 9. Lower Stilling Tank Nozzle Attached for Riveting.

the circulating pump probably has a rotational component which tends to force any undissolved air to the center, a collector pipe is installed at the center of the inlet to the stilling tank to cut out a core from this zone and carry it to the top of the tank to assist in the deaeration. The rest of the flow is divided into two equal parts, the first being allowed to enter the stilling tank in a concentric ring at the inlet flange, the second being carried vertically upward inside of the stilling tank until it is well above the outlet to the working section. The object of this construction is to secure a more uniform flow to the working section. Figure 10 is a view looking into the lower inlet nozzle of the stilling tank. The small central pipe is for the air removal and the large concentric one is for the flow distribution.

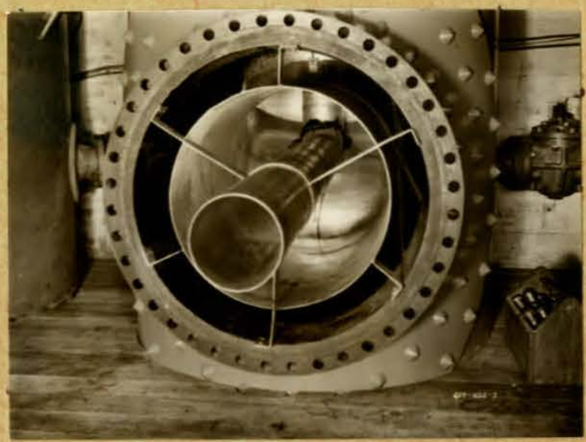


Fig. 10. Inlet Nozzle of Stilling Tank. Small Central Pipe is For Air Removal. Larger Pipe is for Flow Distribution.

Figure 11 is a downward view inside the stilling tank. The large pipe is the flow-dividing riser. The 8-inch conduit seen rising diagonally across the tank is an additional de-aerating pipe placed so as to collect any bubbles that are swept along the top of the pump discharge line.

Fig. 11. Downward View Inside Stilling Tank.

In order to equalize the flow in the stilling tank the friction losses in the two divided circuits are balanced by installing in the upper part of the 30-inch riser a diffuser section for recovering a portion of the velocity head to compensate for the additional losses of the longer flow path. Figure 12 is a view looking upward in the stilling tank showing the bell-mouth discharge of the 30-inch riser with the small deaerating pipe continuing on above it.

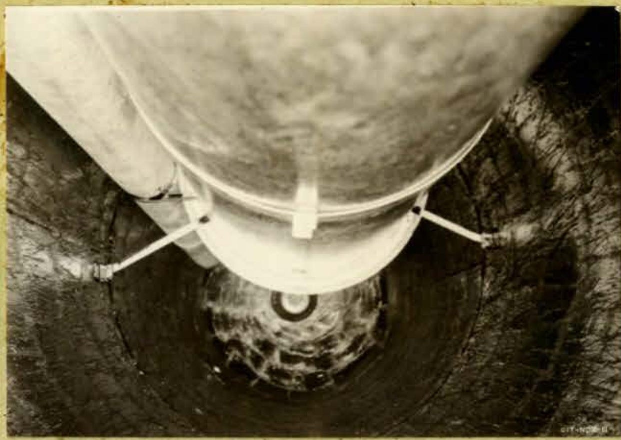


Fig. 12. Upward View Inside Stilling Tank.

(c) Reducing Nozzle and Flow-Straightening Section. Figure 13 shows the straightening section and bell-mouth nozzle which connects the stilling tank to the working test section. This picture also shows the piezometer rings used to measure the pressure drop across the nozzle and hence the velocity of flow in the test section. At the discharge end of the bell-mouth nozzle is seen the square base which is drilled for the direction-finding Pitot tube used to obtain velocity traverses of the flow. Figure 14 shows this section on the test floor as seen from the upstream or tank end. The triangular honeycomb for straightening the flow is installed in the upstream end of this section. The cells are one inch on the side and 10 1/2" long. Figure 15 is a more direct view of this honeycomb showing the type of construction employed.

(d) Working Section. Several different working sections are available for use with the tunnel. Figure 16 shows the simplest of these, a plain steel tube. This illustrates clearly the method of in-

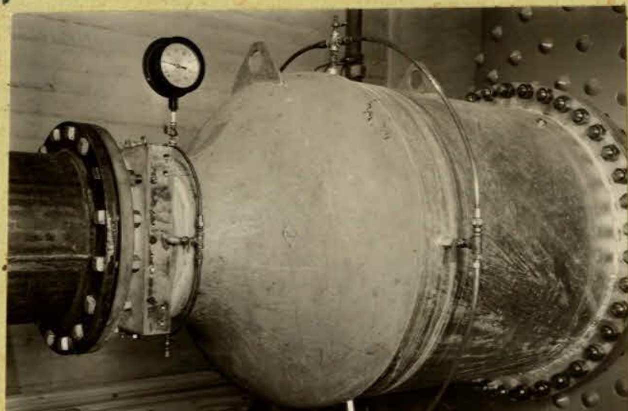


Fig. 13. Flow Straightening Section and Bell-Mouth Nozzle.

Fig. 14. Honeycomb Flow Straightener.

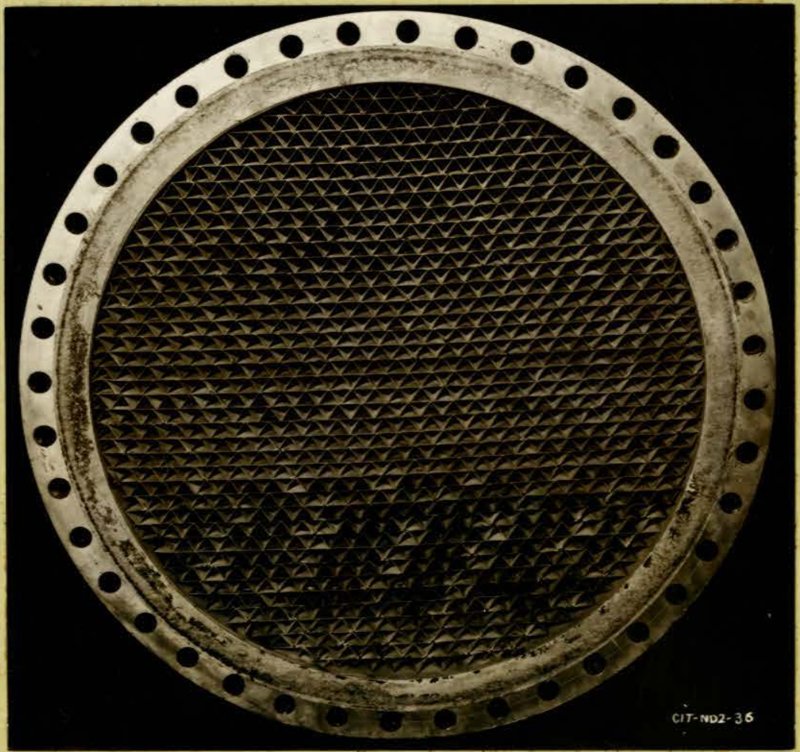


Fig. 15. Honeycomb Flow Straightener.

stallation. The upper end of the working section is bolted directly to the discharge flange of the bell-mouth nozzle. Locating dowels are used to insure precise alignment to avoid disturbance of the flow at this critical point. An unsupported area type neoprene gasket is used which permits metal-to-metal contact of the flanges and eliminates any possibility of gasket material projecting into the flow.

The downstream end of the working section is connected to the diffuser through a Victaulic coupling. This eliminates any mechanical stress on the working section and provides for thermal expansion.

Figure 17 shows a Lucite working section used when complete visual observation is desired. Note that in this photograph the flow is from left to right. In erecting this section a split steel flange is used to hold the Lucite against the face of

Fig. 16. Steel Working Section.

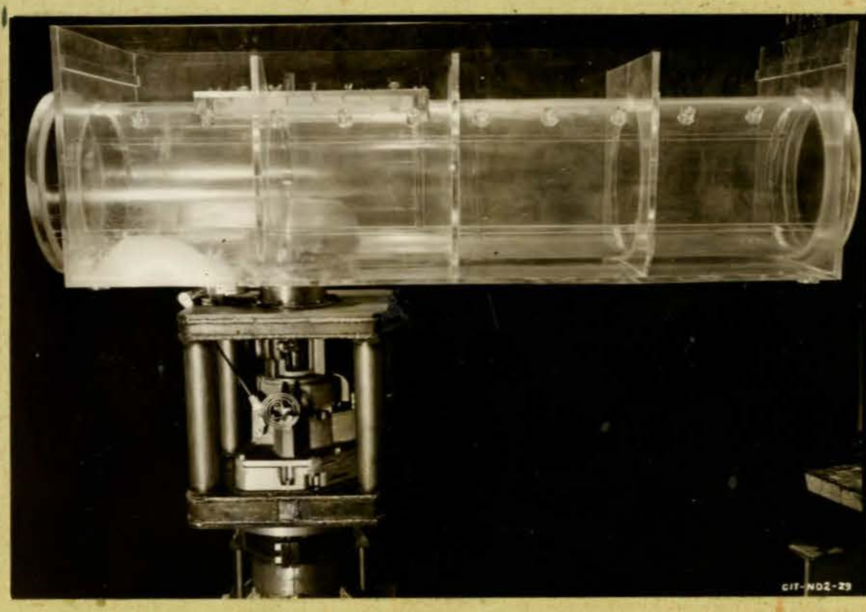


Fig. 17. Lucite Transparent Working Section.

the bell-mouth nozzle; otherwise, the connections are identical with those for the steel section. The square outer box which surrounds the circular working section may be filled with water to eliminate the optical distortion which otherwise interferes markedly with visual observation.

(e) Diffuser Sections. The remainder of the circuit between the downstream end of the working section and inlet to the pump is shown clearly in Figure 3. It is made up of two diffusers, a vane elbow and a straight piece of pipe. Note the simple appearance of the vane elbow in the foreground. The vanes are welded in internally, after which the complete assembly is galvanized.

2. Auxiliary Circuits. Several auxiliary circuits are used in connection with this primary one to obtain the desired operating flexibility. The basic principle upon which they operate is the same as that utilized in the Hydraulic Machinery Laboratory. The water tunnel operates on a closed circuit in a completely filled system; therefore, it is possible to impose other minor flow circuits on this system without disturbing the main flow. This principle is used in obtaining pressure control of the system, as may be seen by referring to Figure 1.

(a) Pressure Regulating Circuit. The regulating circuit pump is installed in an open storage tank. The discharge goes to the stilling tank through the horizontal pipe in Figure 1. Since the system is full, this same amount of water must leave the tank through the bypass valve. This bypass valve is motor-operated and is controlled from the working floor. The pressure in the stilling tank varies with the amount of opening of this bypass valve. When it is nearly closed the stilling tank pressure reaches the maximum head which the circulating pump can develop, i.e., about 150 feet. Opening the bypass valve reduces the head until atmospheric pressure is reached. Since the working section is about 15 feet higher than the valve and since there is a large additional pressure drop in the bell-mouth nozzle, the pressure in the working section under these conditions is considerably below atmospheric. However, if still lower pressures are desired, a booster pump, not shown in this sketch, may be started. The result is that cavitating conditions can be maintained in the working section for any desired test velocity.

(b) Cooling Circuit. In the operation of the tunnel, up to 250 H.P. is continuously put into the system through the circulating pump. This energy is all dissipated into heat; thus unless the system is cooled, the temperature will rise to undesirable values. To maintain a constant viscosity and therefore a constant Reynolds number for testing, this heat must be removed. The method for doing this is also shown in Figure 1. A part of the return flow from the bypass valve of the regulating system is picked up by the cooling-water pump, which circulates it through a forced-draft cooling tower on the roof and returns it to the storage tank. Thus, cooling is obtained by continuously bleeding off hot water from the system and returning an equal amount of cooled water.

(c) Air Eliminating Circuit. To keep the system full at all times and to eliminate any air, the two vertical tanks are provided with bleed lines in their upper heads which go to a Nash Hytor vacuum pump.

C. Instrumental Equipment

The instrumental equipment for use with the tunnel may be divided into groups as follows:

(a) Balance and Force Measuring Equipment
(b) Velocity Distribution Measuring Equipment
(c) Pressure Distribution Measuring Equipment
(d) Models
(e) Photographic Equipment

They will be discussed in this order.

1. Balance and Force Measuring Equipment. As previously outlined, the balance is designed to measure three components of the hydrodynamic forces acting on the model. These are the drag force parallel to the flow, the yaw force normal to the flow, and the moment around the axis of support.

Figure 18 is a schematic diagram of the balance system. Basically it consists of a vertical beam or spindle, supported near the center, with a universal pivot that permits rotation about any axis through this point, but allows no translation. The model is attached rigidly to the top of the spindle. This assembly is prevented from rotating under the action of the hydrodynamic forces by applying restraining moments about three mutually perpendicular axes intersecting at the pivot. These moments are applied by hydraulic pressure through the three sets of pistons and cylinders shown in Figure 18. By orienting these axes so that one is parallel to the flow and two are normal to it, the three restraining moments correspond to the three desired components of the hydrodynamic force system acting on the model.

Fig. 18. Schematic Diagram of Balance System.

In order to measure the forces acting on the model when it is inclined to the flow, the model is actually mounted on a shaft, which forms the core of the balance spindle. By rotating this shaft, the angle of yaw of the model with respect to the flow can be made any desired value. The system of restraining moments acts on the spindle itself. Therefore, the directions of the balance forces do not change as the angle of yaw is varied.

In order to keep the model position accurately fixed in the flow, while the measurements are made, the limits of motion of the hydraulic pistons are restricted to $\pm$ .003 inches. This is equivalent to less than 2 minutes of angle. These small limits require great structural rigidity, both of the spindle and the supporting frame. Figure 19 is a general view of the balance installed on the working floor. It shows how this rigidity has been built into the structure. The whole assembly is mounted on a hydraulic lift for ease in handling and adjusting. It is completely supported by this lift in the working section. In Figure 19 it is seen in the lowered position. The bottom of the Lucite test section is just visible at the top of the picture. The shaft, which supports the model, is seen projecting vertically upward from the top of the balance. This shaft is removable so that various types may be used to meet the varying needs of the different tests. The spindle pivot lies at the center of the bronze ring seen at the top of the structure. The pivot is made up of two sets of three pairs of piano wire. Each set forms three equally spaced elements on the surface of a cone. The two vertices meet in a point on the center line of the spindle. This means that for small deflections this point is the center of rotation for all three moments that are measured.

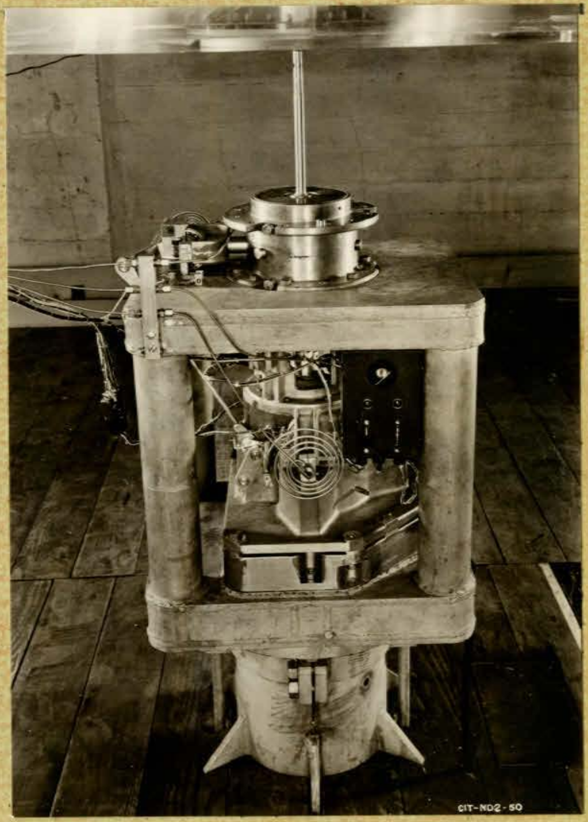


Fig. 19. Water Tunnel Balance. Supporting Lift in Lowered Position.

A water-tight seal is provided between the balance spindle and the working section in the form of a soft rubber cylinder which is reinforced with concentric steel rings vulcanized into it. This construction permits extreme flexibility and at the same time gives a structure which will resist both internal and external pressure. It operates satisfactorily from pressures of 50 pounds per square inch down to the vapor pressure of cold water.

Figure 20 shows the downstream side of the balance in somewhat more detail. The spindle is seen hanging through the hole in the frame. This figure also shows the motor used to adjust the yaw angle of the model. The model-supporting shaft is rotated within the spindle by the worm-wheel sector and the worm, which is driven by the small motor seen in the center of Figure 20. A Veeder counter on the worm shaft indicates the yaw angle of the model to the nearest tenth of a degree. The shaft has a long taper seat which prevents it from moving between adjustments. This seat is broken during adjustments by an air diaphragm acting upon the bottom of the shaft, making it free to be turned by the small motor. It should be noted that this entire system is part of the spindle assembly and hangs from the pivot system. It thus does not affect the force measurements in any way.

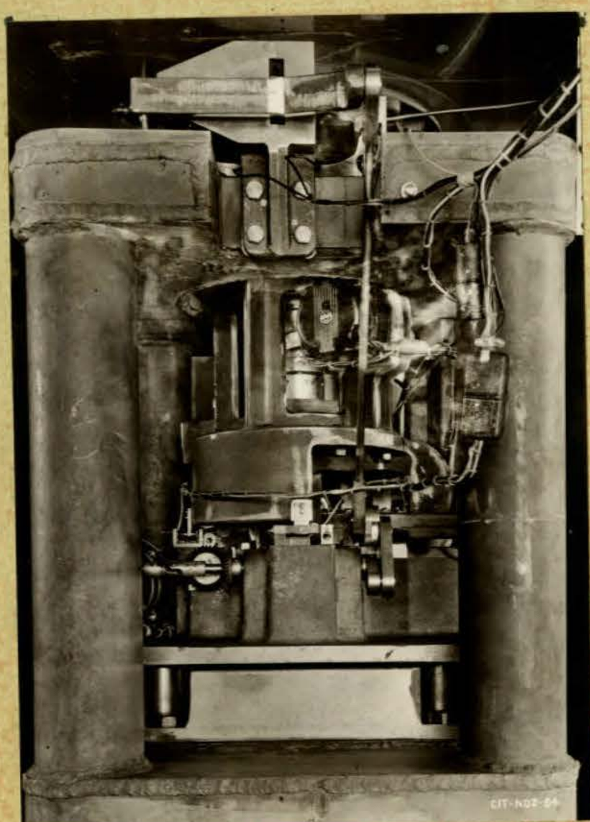


Fig. 20. Water Tunnel Balance. Downstream View.

Figure 21 is a view of the balance as seen from the front, or working side, and Figure 22 is a corresponding view of the opposite side. In these pictures may be seen practically all of the details of the hydraulic cylinder and piston systems used for transmitting the forces from the model to the weighing pressure gauges which measure them. Figure 23 is a diagram of one of these systems. For each of the 3 degrees of freedom a hydraulic cylinder is fixed to the balance frame. Each cylinder is provided with a pair of ground pistons. For each measuring cylinder on the spindle structure two rods are mounted, which engage the two matching pistons. By means of suitable stops, one rod and piston are engaged when the force is in one direction; whereas, if the force reverses the other rod and piston become effective. To eliminate deformation and wear, the contact surface on each rod is a polished ball of Kenna metal, a Tungsten-vanadium-carbide, which bears on a plate of the same material inserted in the piston head. To avoid static fric-

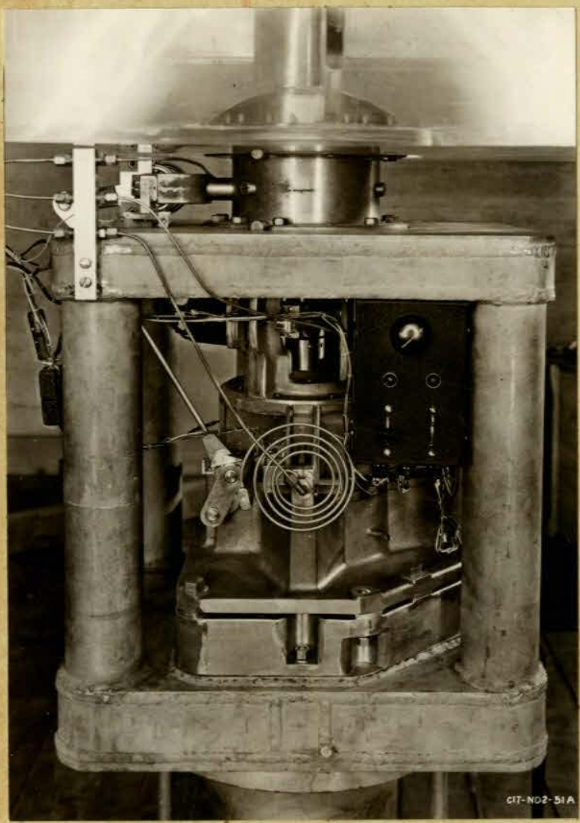


Fig. 21 Working Side View.

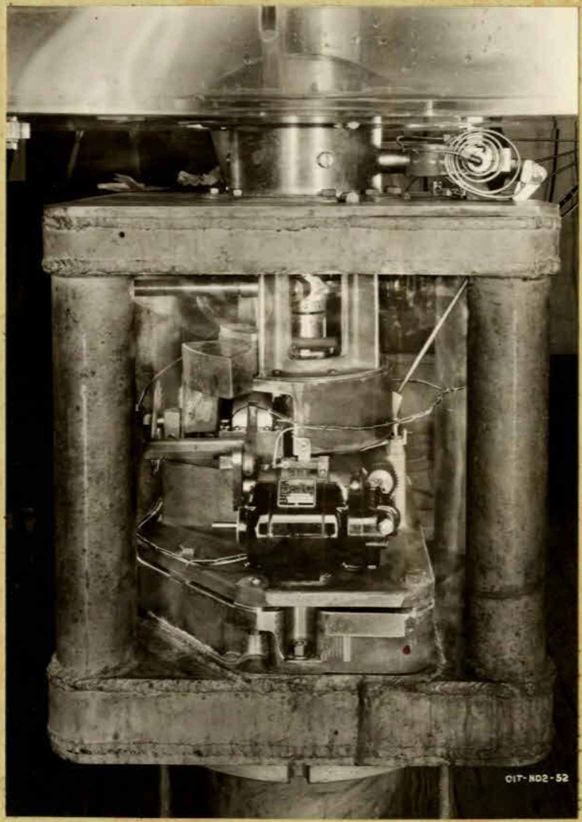


Fig. 22 View Showing Oscillating Motor.

Water Tunnel Balance

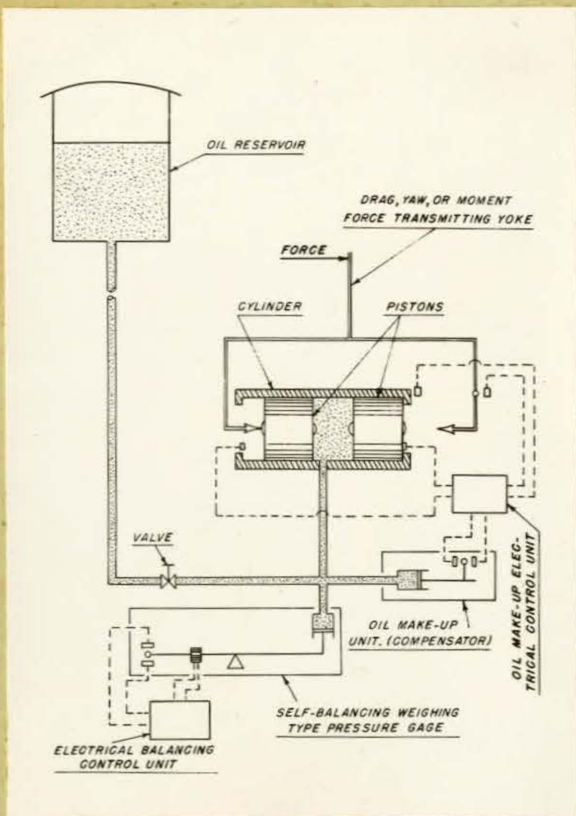


Fig. 23 Diagram of Hydraulic Force- Transmitting System.

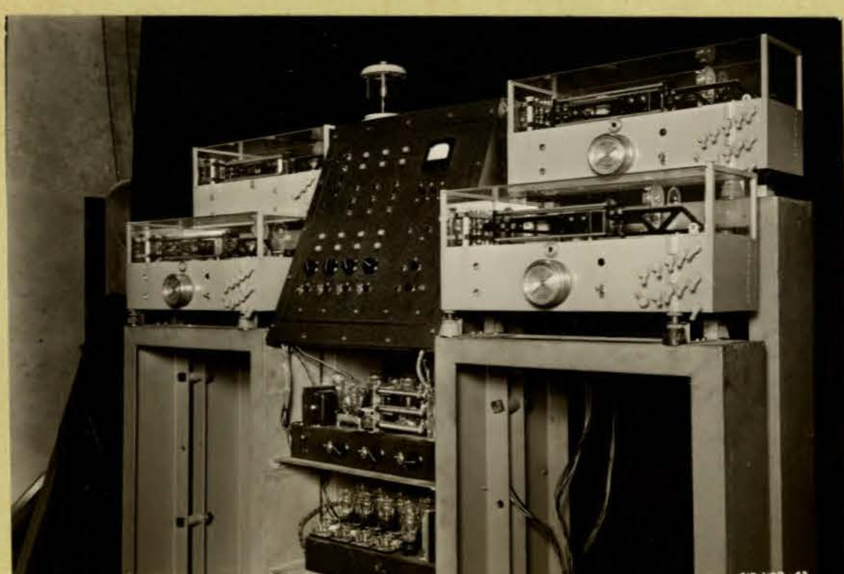


Fig. 24 Instrument Stand.

tion, these measuring cylinders are mounted in bearings and oscillated, while the pistons are restrained from oscillating by stops. Each set, consisting of a cylinder and the two matching pistons, are lapped to precise dimensions, the clearance between the cylinder and the pistons being about 0.00004 inches. The helical coil in the center of Figure 21 is the pressure tubing connecting the oscillating cylinder of the yaw measuring unit to the balance frame. The corresponding coils for the drag and moment units are seen in Figure 22. The motor in the foreground oscillates the cylinders of all three measuring units.

In the upper left hand corner of Figure 21 will be seen the three pressure lines leading to the weighing type pressure gages on the instrument stand. The yaw and drag gages are the two instruments on the right. The moment gage is the lower instrument on the left. The upper left hand instrument is the weighing type manometer for the velocity measurement. Figure 25 is a close-up of the weighing type pressure gage. For details of this construction, see Appendix A, page 671.

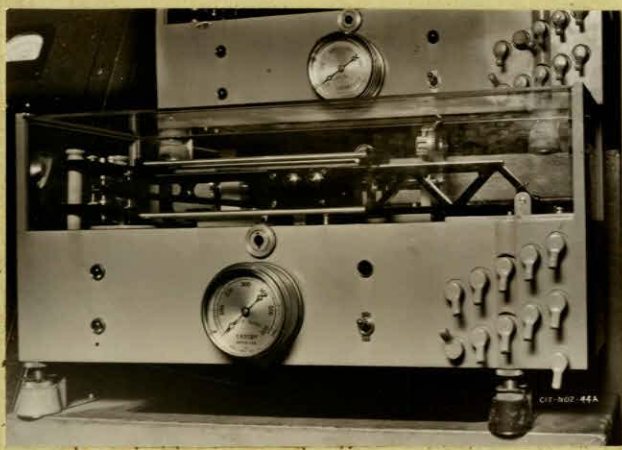


Fig. 25 Close-up View of Pressure Gage.

In the center of Figure 24 will be seen the main control panel for the measuring instruments. All of these four principal gages are of the self-balancing type. Each gage is provided with a set of indicating lights on the control panel to show when equilibrium has been reached. The four balancing motors are controlled by a single master switch on the panel. When a reading is being taken, the operator observes the signal lights until they indicate that all balances are in equilibrium. He then turns off the master switch, thus securing a simultaneous reading from all four gages.

The three weighing type gages, together with their corresponding measuring pistons and cylinders, form three constant volume systems, all of which have small but continuous and unavoidable leakage points at the pistons. To keep such systems operating, it is necessary to supply make-up oil in minute amounts and in such a manner as to not interfere with the readings. This is accomplished by having a compensator unit for each system, driven by a motor which is controlled by contacts on the balance and the gages. These units and the oil reservoir which supplies them are mounted behind the control panel as shown in Figure 26. Figure 27 is a close-up, showing the cover removed from the center unit. Figure 28 shows a single unit and Figure 29 the same unit disassembled.

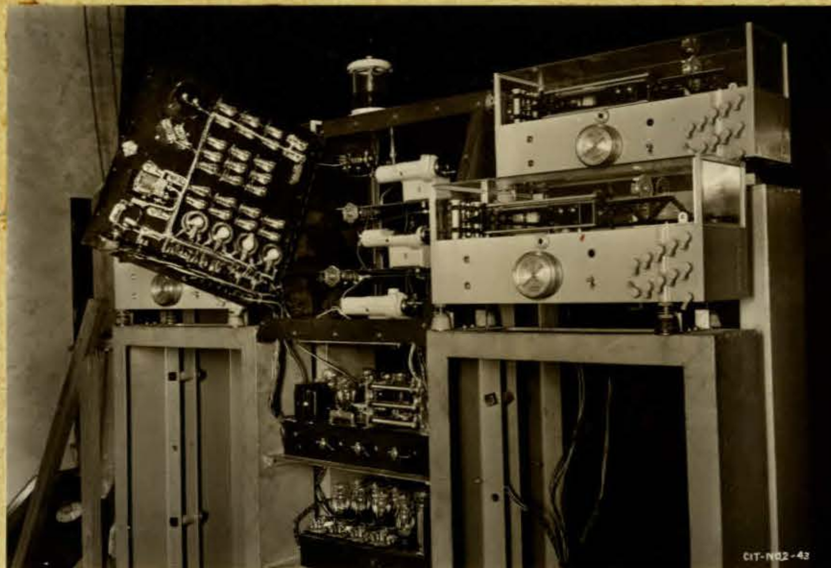


Fig. 26 Instrument Stand - Oil Compensator Units Shown Behind Opened Panel.

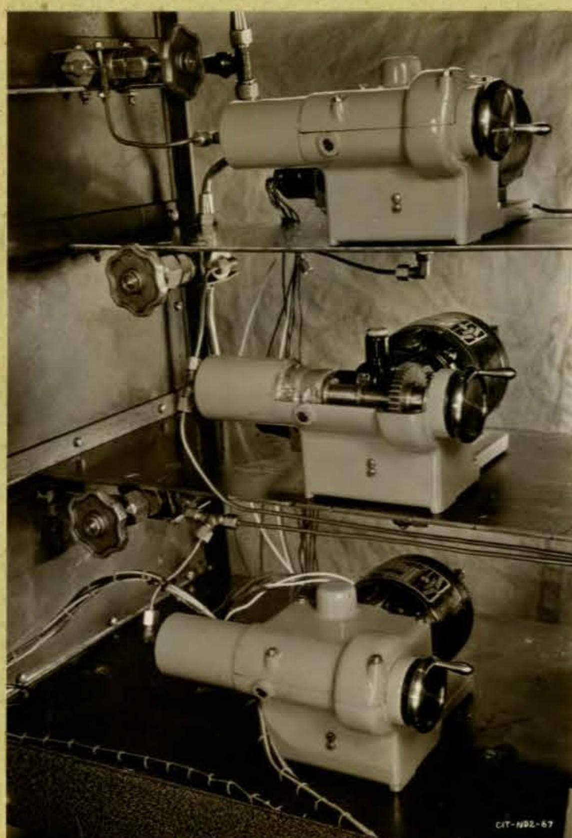


Fig. 27 Oil Compensator Units.

Fig. 28 Oil Compensator Unit.

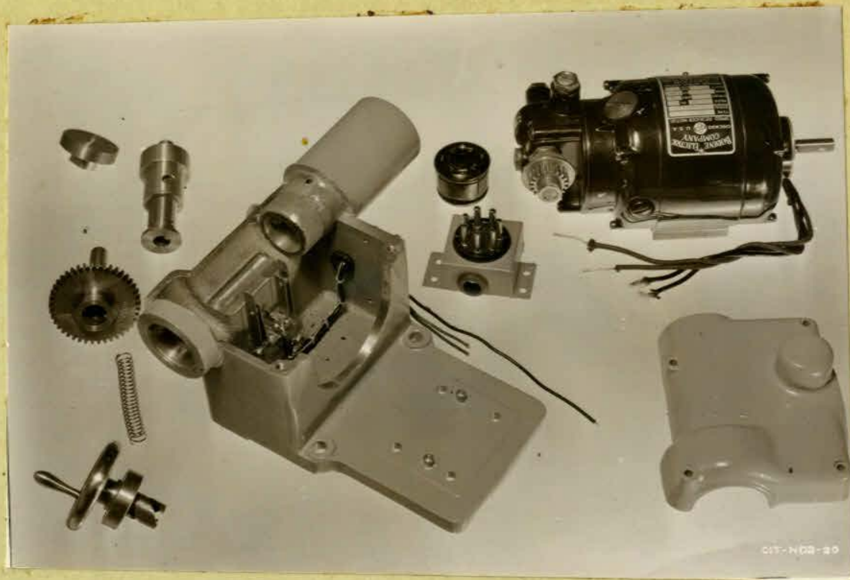


Fig. 29 Disassembled Oil Compensator Unit.

2. Velocity Distribution Measuring Equipment. In order to insure that satisfactorily uniform velocity distribution is obtained in the working or test section, arrangements for velocity profile measurements were made at the discharge of the bell-mouth nozzle. The technique used is that developed in the Hydraulic Machinery Laboratory for determining velocity distributions in pump and turbine volutes and in the connecting piping. A three-hole direction-finding Pitot tube is used. The three holes are drilled radially and lie in one circumferential element of the tube. They are spaced approximately 37 degrees apart. Each hole connects with a separate longitudinal passage in the tube, which terminates in a tubing connector. Lines from these three connectors go to a differential pressure gage. Figure 30 shows this Pitot tube. When the tube is in use it is inserted in the flow with its axis normal to the flow. The passages from the two outside holes are connected to the opposite sides of the differential gage and the tube is rotated until the two pressures are balanced. The bisector of the included

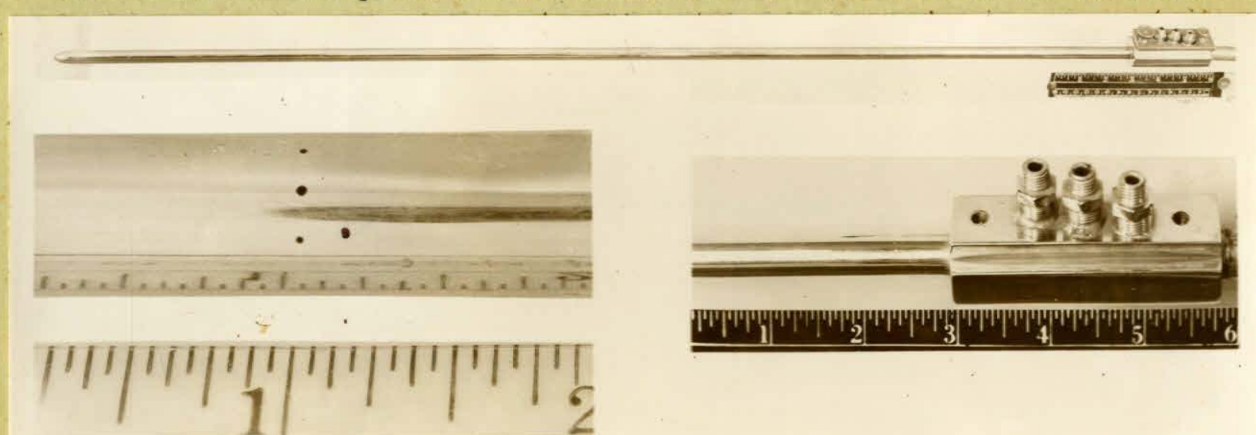


Fig. 30 Three Hole Pitot Tube.

angle between these holes is now pointing directly upstream, and the protractor on the tube fixture reads the angle of the flow, with respect to the flow passage. The angles were so chosen for the hole locations, that in this balanced condition the pressure at the outside holes is the true static pressure. The static pressure is measured by disconnecting one hole from the differential gage and opening that side of the gage to the atmosphere. The third hole, which is on the bisector of the angle between the two outside axes, is now pointing directly upstream. Therefore when it is connected to one side of the differential gage with one of the outside holes still connected to the other side, the resulting reading is the velocity pressure. By moving the Pitot tube across the flow a direction and velocity traverse is obtained. Provisions were incorporated for making five such traverses in the horizontal and five in the vertical direction across the flow. The measuring stations are so arranged that readings can be taken at intermediate points. Figure 31 shows the fixture employed with the Pitot tube for determining the angles of the flow, note the locations of the horizontal traverse lines. Figure 32 is the differential pressure gage used with the Pitot tube. For further details of this technique see "Experimental Determination of the Flow Characteristics in the Volutes of Centrifugal Pumps", by R. C. Binder and R. T. Knapp, Trans. A.S.M.E., Vol. 58, Nov. 1936, pp 549-662.

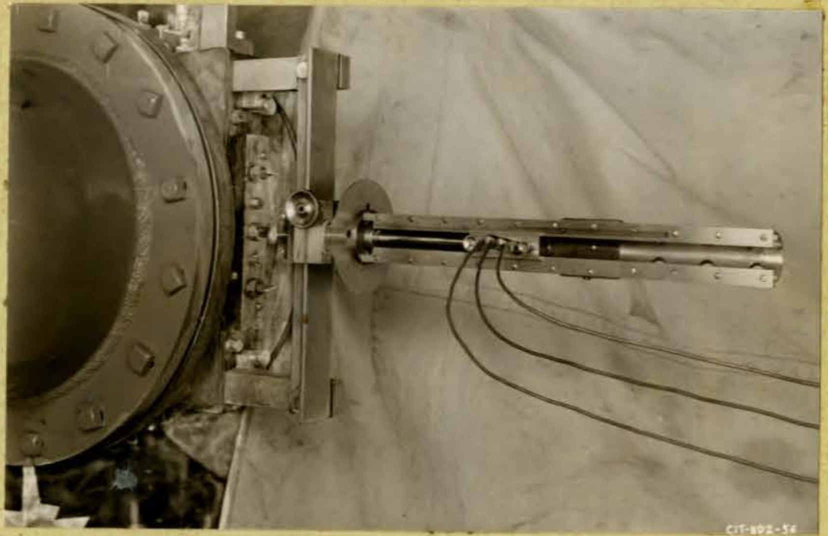


Fig. 31 Indexing Fixture used with Pitot Tube for Determining the Angle of Flow.

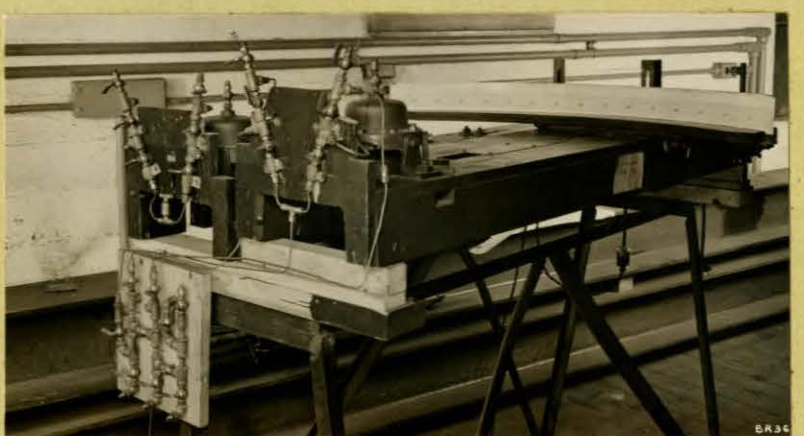


Fig. 32 Differential Pressure Gages used with Pitot Tube. Gage Deflection is Registered Optically on Circular Scale.

3. Pressure Distribution Measuring Equipment. Since measurements are made on the model with a fluid flow having a pressure gradient along the working section and since the size and position of the model affects this pressure gradient, it is necessary to measure the pressure in the working section at closely spaced points along it. For this purpose the multiple differential manometer, seen in Figure 33, is employed. This is an air-water type and uses the pressure at the beginning of the working section for the reference pressure. As will be seen from the figure, this manometer is well-suited for photographic recording. Since the total pressure drop in the working section is of the order of 0.1 or 0.2 of a velocity head, great care has to be exercised in the construction of the piezometer openings to insure that the static pressure alone is measured, without measuring any of the velocity pressure.

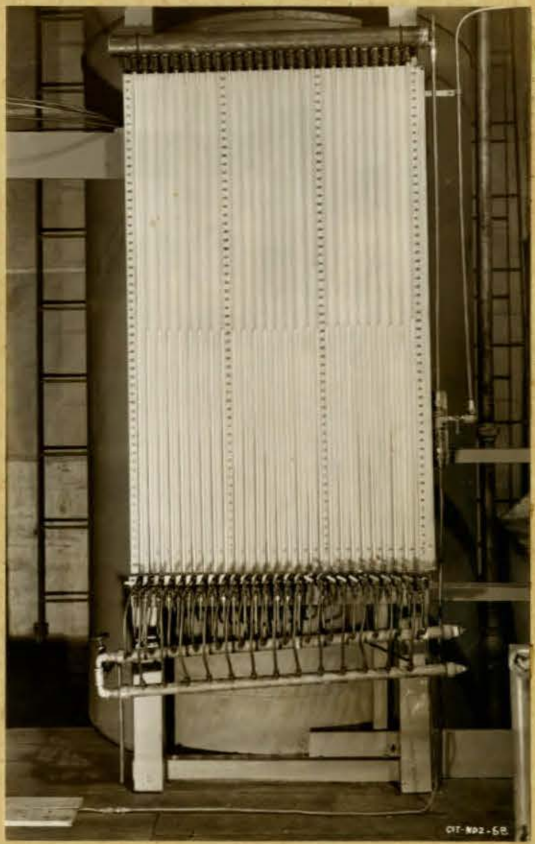


Fig. 33 Multimanometer Board Used to Measure Drop along Working Section.

4. Models. The model to be tested fastens rigidly to the balance spindle shaft, which is provided with a taper end and locking pin for this purpose. An analysis of the probable requirements showed that most of the models to be tested would be circular and would have at least a small cylindrical portion, with widely varying nose, afterbody and tail sections. Two types of construction appeared possible: (a) the making of a complete new model for each shape to be studied; (b) the construction of a series of standard parts from which a wide variety of models could be built up. The latter procedure was chosen as being speedier, more economical, and much more flexible. Figure 34 shows an assembled model and Figure 35 the individual components. The model is assembled around the short cylindrical mounting section having the taper socket for attachment to the balance shaft. A locking pin through the shaft and mounting section, orients the model and holds it firmly to the spindle. Additional cylindrical sections are added until the desired body length is obtained. The necessary nose, afterbody and tail forms are then added and the whole structure locked together with a through-bolt along the axis. The individual sections have tongue and shoulder joints to secure precise alignment. A concentricity of about ± 0.0002 inch has been secured. When a design for a new body is submitted for test a quick survey of the model parts, shows what elements are available and what new parts must be made.

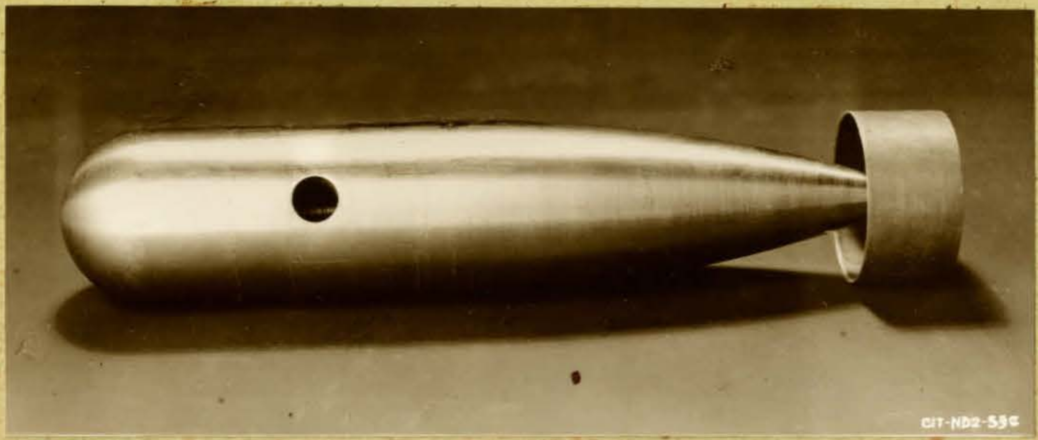


Fig. 34. Typical Model

Fig. 35. Typical Model Showing
Method of Construction and Assembly

In general, the model sections are made of stainless steel to eliminate corrosion and to secure a reasonable hardness to prevent damage from handling. Special sections may be made of brass.

5. Photographic Equipment. To permit visual observations and to facilitate cavitation studies, transparent working sections or sections with observation windows have been constructed. Since cavitation is a very high speed phenomenon, purely visual observations are inadequate; therefore, an Edgerton high speed motion picture camera and flash lamps have been procured. High speed single exposure pictures can also be taken.

IV. OPERATING CHARACTERISTICS OF THE TUNNEL

A. Velocities Obtainable.

The maximum velocity measured to date in the tunnel working section is 72 ft./sec. This was obtained with the dynamometer operating at 2000 r.p.m. and 242 h.p. This does not represent the maximum power and speed available. At this velocity, however, it is very difficult to suppress cavitation on the model at the point of the attachment and on the spindle shield itself; therefore, for the present there seems to be little need of attempting to push the velocity to higher values. The speed of the dynamometer is held constant to ± 1 r.p.m. Since the velocity in the tunnel should vary directly with this speed, variations in velocity of the order of 1/30 of a ft.per sec. are to be expected. No direct measurements of this fluctuation have yet been made. It should be emphasized, however, that this ± 1 r.p.m. represents the maximum deviation of the dynamometer from the mean speed.

B. Velocity Distribution Measurements in the Working Section.

Figure 36 shows a typical velocity traverse across the horizontal diameter of the working section. It will be seen that the velocity over the central 13 inches of the total 14-inch diameter, is constant within ± 0.1 ft./sec. for an average velocity of 71 ft./sec. Simultaneous measurements of the direction of the flow indicated that with no flow-straightening devices, there was a slight amount of rotation. To eliminate this, the honeycomb shown in Figs. 14 and 15 was installed in the flow straightening section.

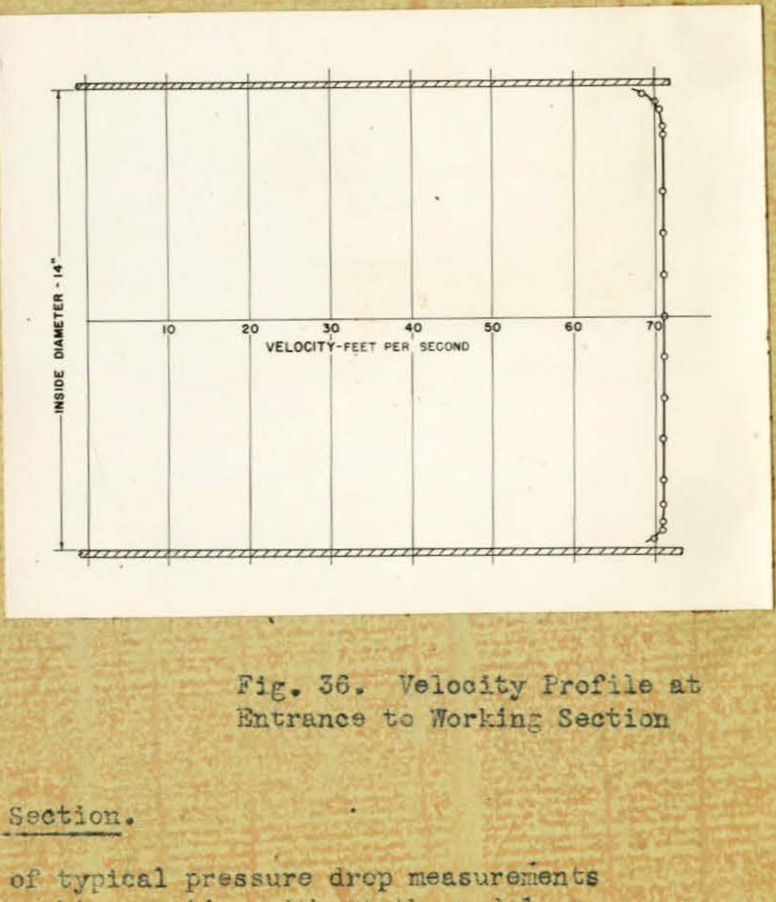
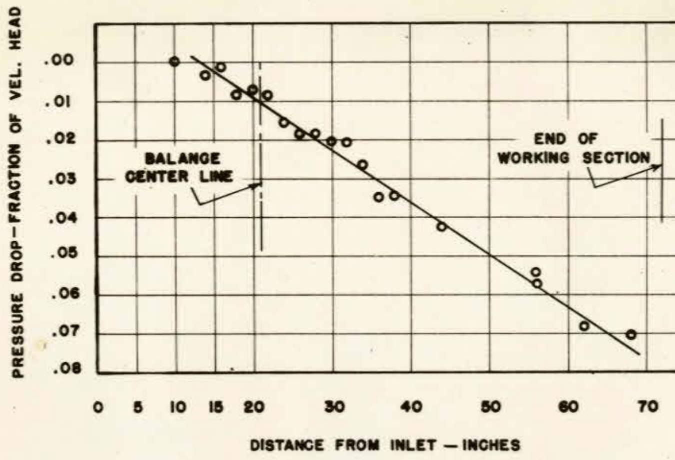


Fig. 36. Velocity Profile at Entrance to Working Section

C. Pressure Drop in Working Section.

Figure 37 shows a series of typical pressure drop measurements taken along the length of the working section without the model or spindle shield being present, but with the 9/16" spindle in the flow.

Fig. 37



PRESSURE DROP ALONG WORKING SECTION

It will be seen that the pressure drop is linear and that the equivalent friction coefficient, f, is about .019 for the normal pipe friction formula:

$$H = f \frac{l}{d} \frac{V^2}{2g} .$$

This run is for the Lucite test section, which is very smooth. Since the Reynolds number of the working section is larger than 3 million at 30 ft. per sec., this pressure drop appears somewhat excessive on the basis of friction alone. However, the larger part of it is probably due to the development of the boundary layer and the consequent rearrangement of the velocity distribution.

D. Balance Sensitivities.

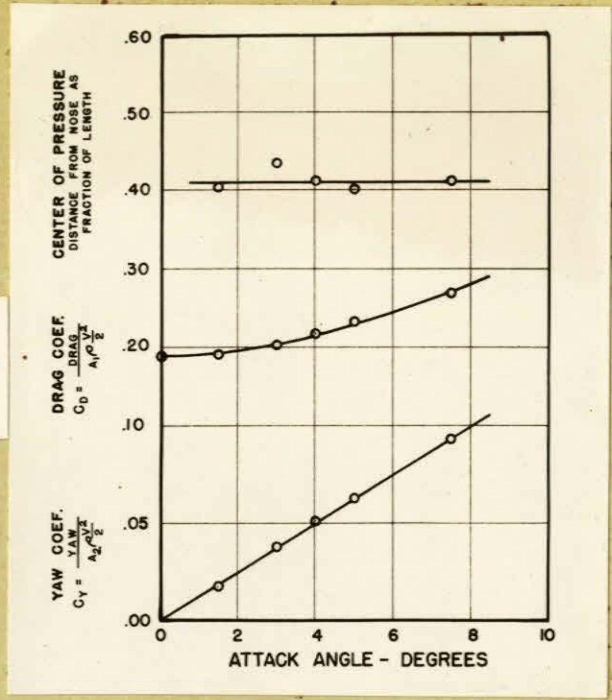
In discussing the sensitivity of the balance system, two characteristics must be noted; the first is sensitivity defined as a change in the reading on the pressure gauge per unit change in force on the model. On this basis for the yaw and drag measurements, one dial division corresponds to .005 pounds force on the model. For the corresponding moment readings one dial division corresponds to .01 inch-pounds torque on the model. The second characteristic is responsiveness, which is defined as the magnitude of the minimum impressed force on the model necessary to cause a change in the gauge readings. At the present time this responsiveness is approximately .02 pounds for yaw and drag measurements on the model and .04 inch-pounds for moment. It is expected that these latter quantities will be reduced to one-half or less of their present values as the balance operation is perfected.

E. Typical Results of Model Tests.

Due to the confidential nature of the problems being studied it seems undesirable to include any detailed discussion of the model tests

Fig. 38.

TYPICAL PERFORMANCE CHARACTERISTICS
2" PROJECTILE
VELOCITY = 31 FT. PER SEC.



made to date. Figure 38 shows the results of a test on one of the current models. In this figure the drag coefficient is based on the cross sectional area, the yaw coefficient on the lateral projected area, and the distance from the nose to the center of pressure is given as the fraction of the length.

V. POLARIZED LIGHT FLUME.

One additional piece of equipment available in this laboratory for the study of the flow around submerged bodies is the polarized light flume. The construction of this piece of equipment was made possible through the courtesy of Dr. Davis R. Dewey II, formerly of the Massachusetts Institute of Technology, who supplied the necessary information concerning this new technique. The general construction of this flume is shown in Figure 39. The entire flow circuit has either brass

Fig. 39.
Polarized
Light Flume.

or glass surfaces to eliminate corrosion encountered with the fluid.

The fluid circulated is water containing .2 per cent weight of Bentonite in suspension. Bentonite has the asymmetrical optical and physical properties required for the production of streaming double refraction. The observation section is a rectangular channel 6" wide and 12" deep, having glass sides and bottom. Velocities up to about 10 ft./ sec. can be obtained. The flow to be studied is made visible by projecting a beam of light across it through a pair of 12-inch polaroid discs. In this installation the discs are circularly polarized and are oriented to produce a dark field with no flow. Although this type of equipment is basically designed for two-dimensional flow studies, it has been found very useful in furnishing qualitative ideas concerning three-dimensional flow around submerged bodies. It is very helpful in investigating interference phenomena, the cause and location of separation or flow instabilities and the behavior of the boundary layers. Figure 40 is a time exposure of a model in the flow. In this figure the details of the flow are lost because of the length of the exposure, although indications of the boundary layer are present.

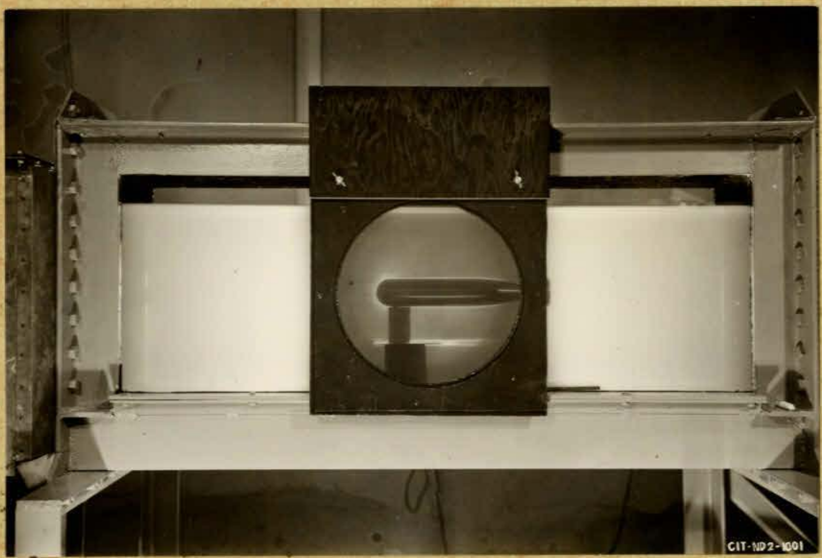


Fig. 40 Time Exposure of Flow Around Model in Polarized Light Flume.

Figures 41 and 42 are single flash photos showing details of the flow and turbulence structure. It must be remembered that care is necessary in interpreting these results, both because the flow is three-dimensional, whereas the optical effect is an integration of the entire path, and because the pattern produced is a shear pattern and not one of streamlines. Nevertheless, it is felt that this new method of flow investigation offers extensive possibilities, which to date have been largely unexplored.

Fig. 41. Single Flash Picture of Flow Around Nose of Model in Polarized Light Flume.

Fig. 42. Single Flash Picture of Flow Around Tail of Model in Polarized Light Flume.